Miniature Vector Laser Magnetometer Measurements of Earth's Field

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***Abstract* - The Miniature Vector Laser Magnetometer (MVLM) measures static and time-varying magnetic field components over the range of +/-65,000 nT with a sensitivity of 10 pT rms per root Hertz and an accuracy of +/-1 nT per component. The MVLM incorporates both scalar and vector modes that each extract magnetic field information from a single laser-pumped helium cell sensor. Observations of the environmental magnetic field components and scalar measurements of Earth's magnetic field have been made using the breadboard instrument at the Polatomic Test Facility. The instrument is currently in the third year of development under the NASA Instrument Incubator Program.**

I. INTRODUCTION

The Miniature Vector Laser Magnetometer (MVLM) is being developed to meet the scientific and environmental requirements of future Earth science missions. The instrument operates over the full range of Earth's magnetic field (±65,000 nT) and incorporates vector and scalar modes. The design and operation were described in the 2003 Earth Science Technology Conference Proceedings [1]. Functional block diagrams of the Electronics Unit and Sensor Unit are shown in Fig. 1 and 2.

The MVLM utilizes single-line laser pumping of a helium cell sensing element and its operation is based on the principles of optically pumped He^4 in the metastable triplet state. The MVLM measures the vector components and scalar reference value in the same sensing volume. Vector measurements are made using the Bias Field Nulling (BFN) technique [2] and reference scalar measurements are obtained using the resonance technique of Optically-driven Spin Precession (OSP) [3].

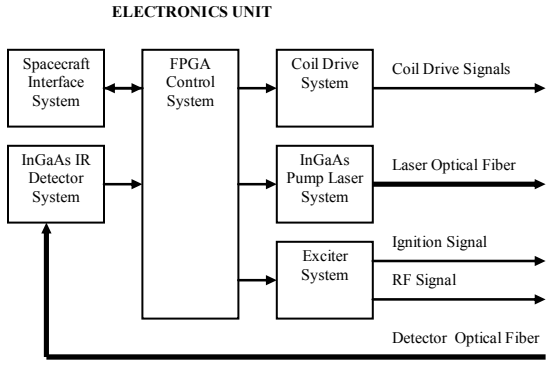

Fig. 1. MVLM Electronics Unit block diagram.

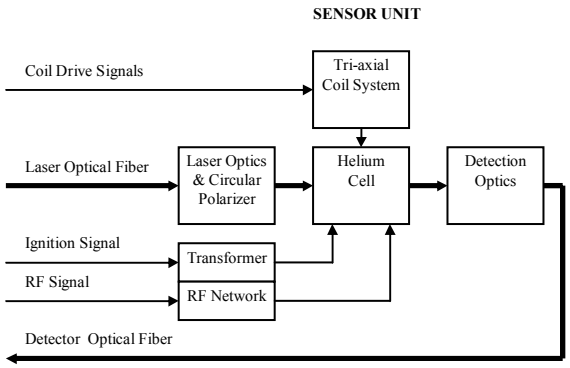

Fig. 2. MVLM Sensor Unit block diagram.

The design is configured for Earth science applications and can greatly reduce required spacecraft resources by replacing a three-fluxgate vector package and its reference scalar magnetometer with a single high performance instrument.

Observations of Earth's magnetic field were made using the breadboard MVLM instrument at the Polatomic Test Facility. Vector measurements and scalar measurements were obtained using the single breadboard MVLM Sensor Unit. This preliminary data demonstrates the functionality of the instrument.

II. TEST CONFIGURATION

The MVLM instrument tests were performed at the Polatomic Test Facility on the University of Texas at Dallas campus. This facility is a former U.S. Coast and Geodetic Survey magnetic observatory and consists of a main instrumentation building and four outlying non-magnetic sensor test buildings. The facility is used for testing high-performance magnetometer systems. The MVLM Sensor Unit was installed level and oriented to geographic North in a sensor test building 30 meters from the main instrumentation building. The breadboard instrument consists of the modules shown in Fig. 1 and 2. For these tests, free-space optics were used and the laser and IR detector were mounted with the Sensor Unit.

The Sensor Unit, shown in Fig. 3, contains a 6 cm^3 helium cell, triaxial coil system, free-space laser optics, and InGaAs IR detector. The RF matching network is currently

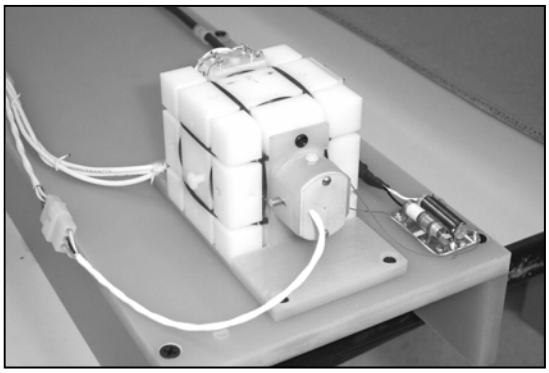

Fig. 3. MVLM breadboard Sensor Unit.

mounted on the test bench to the right of the coil form. All materials near the sensor are magnetically clean. The 6 x 6 x 6 cm coil form and housing are constructed of Delrin. Temperature compensation was added to the breadboard Sensor Unit to correct the coil constant for the linear coefficient of expansion of the tri-axial coil form. Suitable coil form materials have been identified for the Flight Unit prototype.

A GPS system was used to provide the location of the Sensor Unit at the coordinates shown in Table 1. The tests were conducted May 3-6, 2004 and the temperature range over the course of these measurements was 16° to 27° C.

Table 1. MVLM Instrument Location.

Latitude	N32.981
Longitude	W96.753
Height MSL	207m

Measurements of the environmental magnetic field were made in vector and scalar modes and compared to a high - performance Polatomic Reference System which was operating continuously during all tests. The Reference System was located in a sensor test building 23 meters East of the MVLM Sensor Unit to prevent magnetic interaction. This magnetometer system is based on Polatomic's laser-pumped P-2000 and AN/ASQ-233 military technology. The system operates in a two-channel Magnetically-driven Spin Precession (MSP) scalar resonance mode with common-mode noise rejection. The instrument has a frequency response of 50 Hz, baseline noise level of 0.2 $pT_{rms}/\sqrt{Hz}$, and an accuracy of 0.1 nT.

The field information from the MVLM and Reference System magnetometers was continuously transmitted through RS-232 serial output ports at 432 Hz. A National Instruments data acquisition system running LabVIEW was used to record and monitor the data.

III. VECTOR MEASUREMENTS

The MVLM Electronics Unit modules were configured for vector mode operation. The vector components of Earth's magnetic field were recorded over a 24 hour period and are shown in Fig. 4. The total field resulting from the vector components is shown in Fig. 5 along with the scalar data obtained from the Reference System 23 meters away.

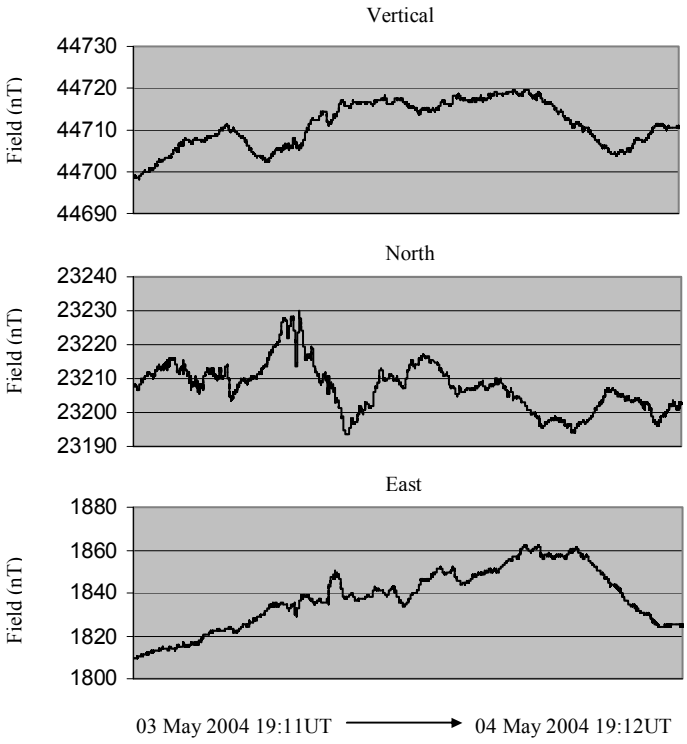

Fig. 4. MVLM vector measurements of Earth's field.

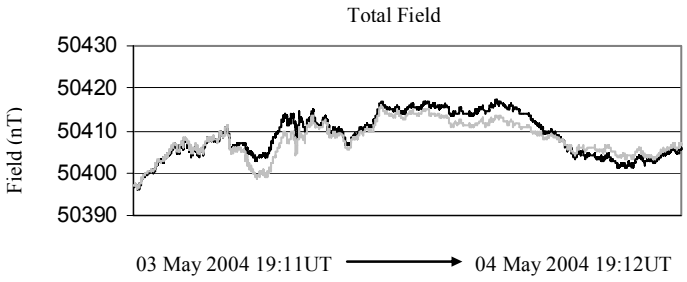

Fig. 5. MVLM total field (black trace) and scalar reference system (gray trace) measurements.

The vector data was compared to the IGRF-2000 Geomagnetic Model [4]. The International Geomagnetic Reference Field provides a model which gives an approximation, near and above the Earth's surface, to that part of the Earth's magnetic field which has its origin inside the surface. As with any geomagnetic model, local field

variations are not accounted for. The coordinate locations from Table 1 were used for the calculations. The MVLM data is consistent with the values derived from the model.

Table 2. IGRF-2000 Geomagnetic Field Calculations

Parameter	MVLM	IGRF-2000
Total Field	50410 nT	50608 nT
Inclination	62.6 Deg	62.3 Deg
Declination	4.5 Deg	4.8 Deg
North Component	23200 nT	23433 nT
East Component	1840 nT	1965 nT
Vertical Component	44710 nT	44813 nT

MVLM data was also recorded at 432 Hz to illustrate the bandwidth capabilities of the instrument. Fig. 6 shows the magnitude of the vertical component of the environmental 60 Hz at the Polatomic Test Facility.

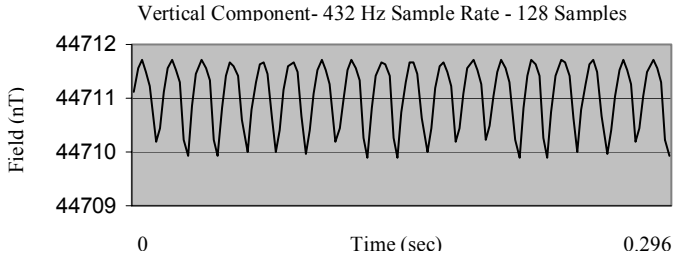

Fig. 6. MVLM vertical component recorded at 432 Hz.

Noise measurements of the environment and sensitivity evaluations using the MVLM were made during the tests. The spectral noise density shown in Fig. 7 was obtained during monitoring of the three vector components of Earth's field. The baseline noise level is 8 $pT_{rms}/\sqrt{Hz}$ as shown in the plot above 2 Hz. The resultant spectral noise density due to environmental 60 Hz is slightly greater than 1000 $pT_{rms}/\sqrt{Hz}$. A major environmental disturbance was detected at 0.06 Hz. These micropulsations in this region of atmospheric noise are typically from solar plasma-magnetosphere interactions

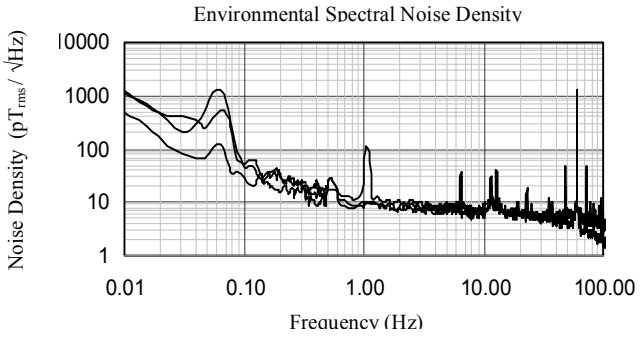

Fig. 7. Environmental spectral noise density.

IV. SCALAR MEASUREMENTS

One of the exciting features of the MVLM is the capability to obtain both vector data and high-accuracy scalar data from the same helium sensor. The scalar feedback loop is a null sensing control loop as is the vector control loop. The scalar electronic system detects and tracks the Larmor frequency (28 Hz/nT). The vector electronic system detects and tracks the error signal resulting from the modulation of absorption in the cell. Since the Larmor frequency is based on fundamental constants, the scalar's absolute accuracy is about 100 times better than that of the vector measurement.

The MVLM Electronics Unit was configured for Optically-driven Spin Precession (OSP) scalar mode operation. No changes are required to the Sensor Unit when switching modes. In scalar mode, the measurements are made by pulsing and tracking the laser at the Larmor resonance frequency which is directly proportional to the ambient magnetic field. A feedback system is presently being designed to concurrently lock the helium pumping laser wavelength loop and the OSP Larmor frequency resonance loop. The scalar value of Earth's magnetic field was recorded over a 4 hour period and is shown in Fig. 8 along with the scalar data obtained from the Reference System. The MVLM successfully demonstrated this mode of operation. The fixed 3 nT gradient and small field differentials are due to the 23 meter separation distance between the MVLM Sensor Unit and Reference System.

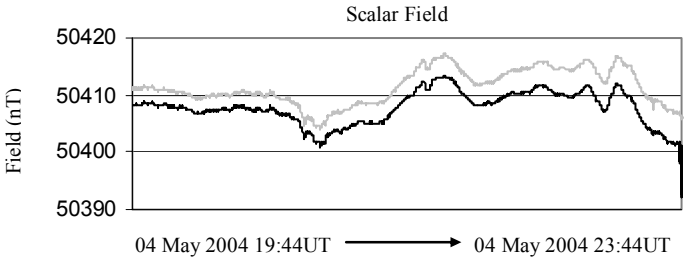

Fig. 8. MVLM OSP mode (black trace) and Reference System (gray trace) scalar measurements.

Noise and sensitivity measurements were also made during the scalar tests. The spectral noise density was obtained during the monitoring of Earth's scalar field and was 8 $pT_{rms}/\sqrt{Hz}$ above 2 Hz. The scalar noise density was very consistent with the noise density measured in vector mode.

V. SUMMARY

Observations of Earth's magnetic field were made using the breadboard Miniature Vector Laser Magnetometer (MVLM) instrument at the Polatomic Test Facility. Vector measurements and scalar measurements were obtained

using the single MVLM Sensor Unit. This preliminary data demonstrates the functionality of the instrument. The MVLM instrument goals are ±1 nT per component accuracy over a dynamic range of ±65,000 nT and a sensitivity of 10 $pT_{rms}/\sqrt{Hz}$. The dynamic range and sensitivity requirements have been demonstrated. A test plan for calibration of the instrument is currently being developed.

The calibration parameters of the vector magnetometer are determined by the use of the scalar reference measurement which measures the magnitude of the magnetic field to an accuracy of better than 0.001%. Nine coefficients are required to calibrate the vector magnetometer. These consist of three offsets, three scale factors, and three non-orthogonality angles. These coefficients can be determined by the scalar magnetometer reference and by exposing the vector instrument to an external magnetic field such as Earth's field. The instrument is oriented in different directions relative to the magnetic field. The data set is a constrained minimization problem which can be solved by several established numerical procedures developed at Polatomic. These techniques will allow the vector instrument to be calibrated to a precision of ±1.0 nT/component. Accuracy and stability tests using the calibrated MVLM will be performed this year.

ACKNOWLEDGMENT

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